Preparing for the X Games of Science

Experiments on the world's most energetic laser will advance astrophysics, planetary physics, and other high-energy-density research.

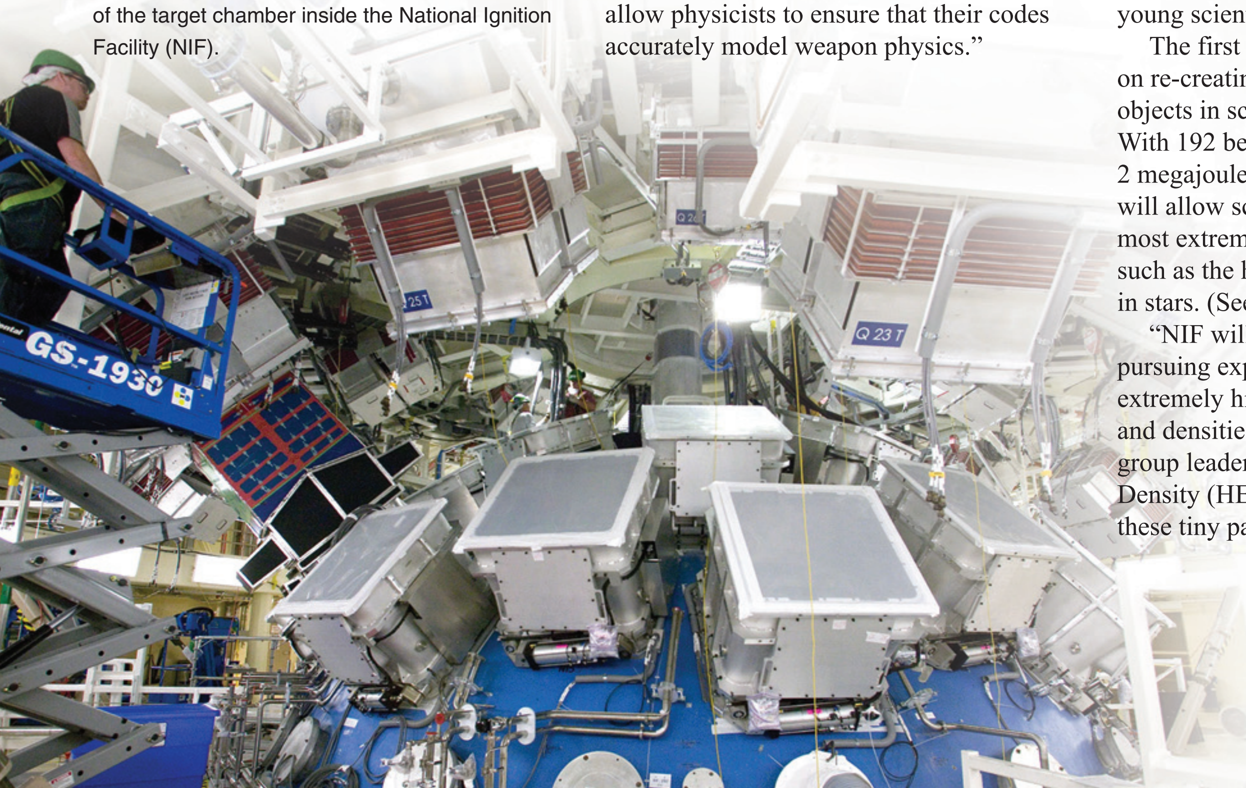
THE National Ignition Facility (NIF), the world's most energetic laser, is more than 90 percent complete, and scientists are preparing for the first experiments, which will begin in 2008. NIF's primary mission is to field experiments in support of the National Nuclear Security Administration's (NNSA's) Stockpile Stewardship Program, which ensures the continued reliability and safety of the nation's nuclear weapons.

"NIF experiments are an essential component of the nation's stockpile assessment and certification strategy," says Ed Moses, associate director for NIF Programs. "It is the only laboratory setting in which we can examine the physical processes that occur when nuclear weapons unleash their immense explosive power. The high-fidelity data acquired in these experiments will improve computer simulations of weapon performance and allow physicists to ensure that their codes accurately model weapon physics."

In addition, NIF will provide researchers from universities and Department of Energy national laboratories unparalleled opportunities to explore the frontiers of basic science. A significant percentage of the first NIF shots will be devoted to basic research in areas such as astrophysics, planetary physics, hydrodynamics, nonlinear optical physics, materials science, and inertial confinement fusion. "Basic science research helps us understand the universe in a fundamental way and then often leads to technological advances," says Moses. "It also provides the Laboratory with an opportunity to recruit outstanding young scientists."

The first basic science studies will focus on re-creating the properties of celestial objects in scaled laboratory experiments. With 192 beams delivering up to 2 megajoules of ultraviolet energy, NIF will allow scientists to explore some of the most extreme conditions in the universe, such as the hot, dense plasmas found in stars. (See the box on p. 6.)

"NIF will offer new opportunities for pursuing experimental science under extremely high temperatures, pressures, and densities," says Bruce Remington, group leader in the NIF High-Energy-Density (HED) Program. "By creating these tiny parcels of plasmas under HED



A worker helps complete the upper hemisphere of the target chamber inside the National Ignition Facility (NIF).

The entrance to the stadium-size facility that houses NIF.

conditions, we can better understand the physical processes that until now we've only been able to observe from afar."

Remington points out that researchers are confident the laser will be an effective HED platform because the 18-month-long NIF Early Light campaign was an unqualified success. This effort, completed in 2004, used the first four finished beams, called a quad, to conduct more than 400 shots while testing every component and system. Many of the 150 shots devoted to science led to published papers in top peer-reviewed journals, such as *Physical Review Letters*. "The laser performance during the NIF Early Light campaign was of startling quality," says Remington. "It worked incredibly well, which is promising for experiments we'll be doing on the completed facility."

Spreading the Word

NIF experiments will help scientists understand the mechanisms at work in new stars, supernovae, black holes, and the interiors of giant planets. Livermore researchers have long been interested in the physical processes of stars because the primary mechanism involved in producing stellar energy is thermonuclear fusion—a process that is central to the Laboratory's national security mission. Since its founding in 1952, the Laboratory has advanced astrophysics by applying expertise in HED physics and computer modeling to examine the atomic processes that occur in these regimes. (See the highlight on p. 24.)

Numerous scientific organizations have cited the potential payoff from experiments on NIF and other HED facilities, such as the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics and the Z machine at Sandia National Laboratories in New Mexico.

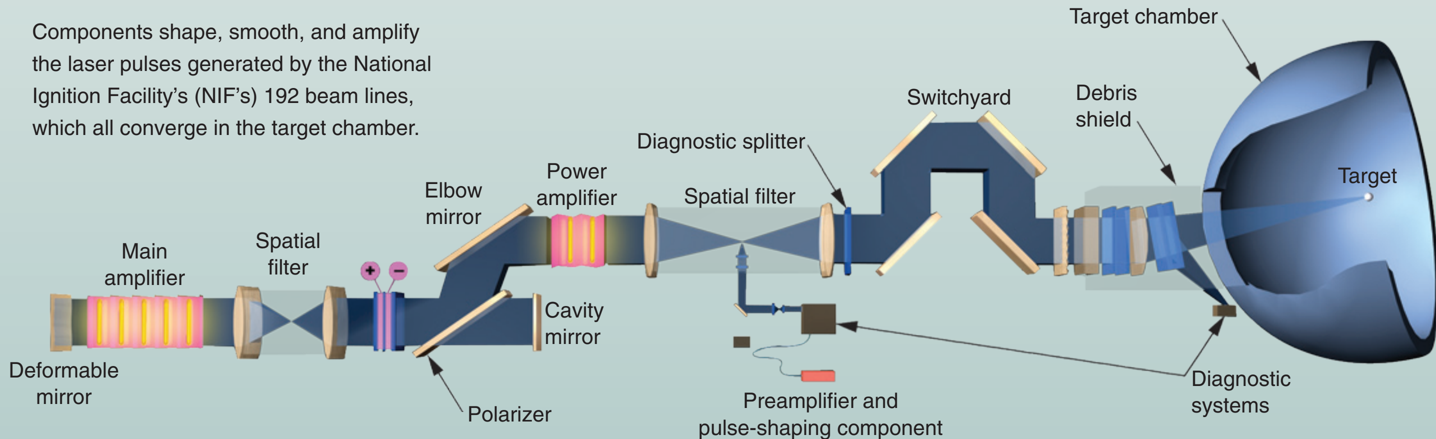
Inside the National Ignition Facility

The National Ignition Facility (NIF) is the world's largest laser facility, and the combined power of its laser beams makes it the most energetic. NIF's 2 megajoules of energy—in a pulse of just a few nanoseconds—is comparable to about 500 trillion watts of power.

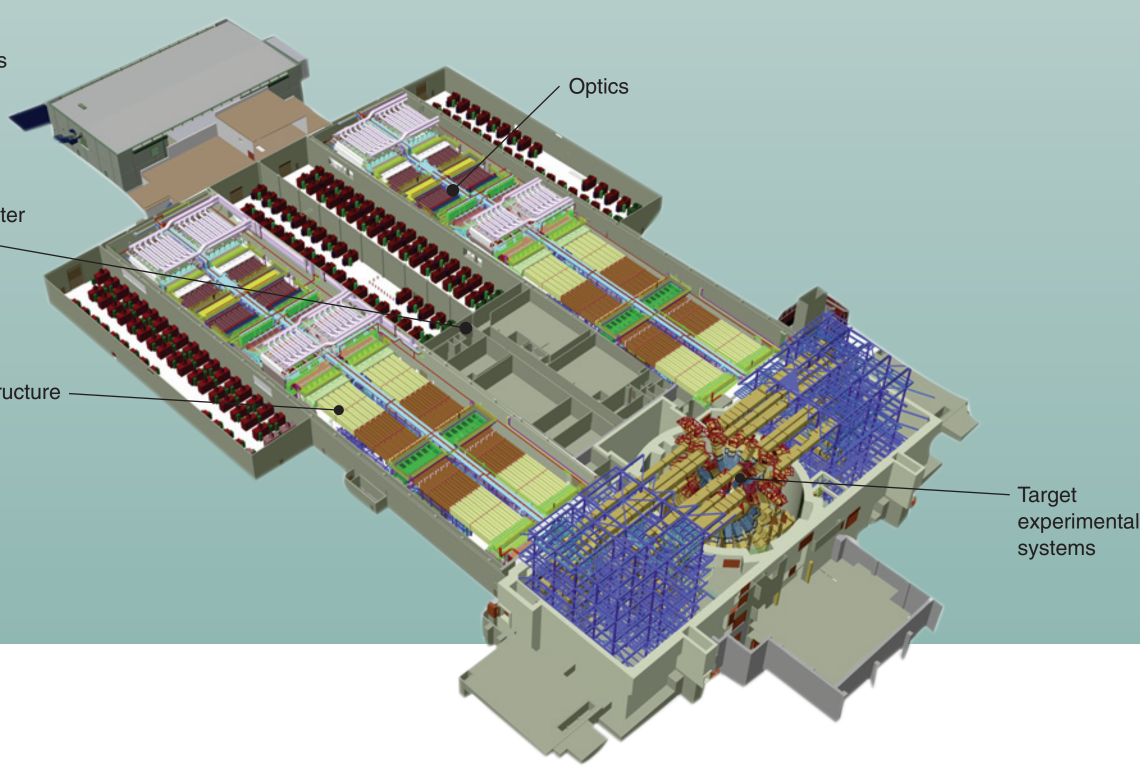
Inside NIF's stadium-size building, laser components shape and smooth an initial pulse, amplify it more than a quadrillion times, and direct it at a tiny target precisely centered in the target chamber. This process is replicated simultaneously 192 times, with all beams converging on the target chamber. More than 100 diagnostic tools can be trained on the target chamber to capture information about each experiment. According to Ed Moses, associate director for NIF Programs, NIF's impressive capabilities resulted from technological advances in laser systems, materials science, and engineering. "Without these breakthroughs," says Moses, "NIF would be far less capable or perhaps could not have been built at all."

The idea for NIF grew out of a decades-long effort to generate self-sustaining nuclear fusion reactions in the laboratory. Theorists, supported by years of experiments, have defined the temperature and pressure conditions required to compress and heat a capsule of deuterium–tritium fuel so that the fuel ignites and burns to produce energy gain. With these capabilities, NIF experiments will create physical regimes never before seen in a laboratory setting.

Components shape, smooth, and amplify the laser pulses generated by the National Ignition Facility's (NIF's) 192 beam lines, which all converge in the target chamber.



This cutaway drawing shows the interior layout of NIF.



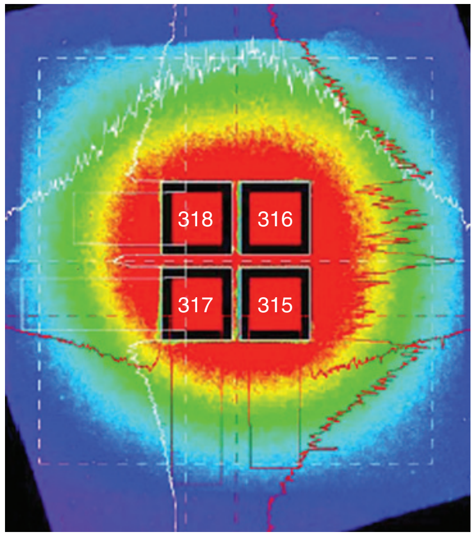
The National Research Council has termed experiments on these HED facilities "the X Games of contemporary science."

NIF managers are devising a detailed plan for engaging external participation and collaboration. Their goal is to turn NIF into a premier international center for experimental science, much like the Advanced Photon Source at Argonne National Laboratory or the Stanford Linear Accelerator Center.

"A broad scientific user community is critical to NIF's success," says Dick Boyd, science director of NIF Programs. "We're spreading the word about experimental opportunities." Boyd and other Livermore scientists plan to speak at American Physical Society meetings and other venues to outline NIF's capabilities and encourage participation. "We want to involve researchers who might not otherwise consider experiments on NIF," says Boyd.

Each proposal will undergo peer review by recognized experts in that particular field as well as a technical review by NIF staff. The most promising proposals will be forwarded to an independent committee of scientists from Livermore and other research centers and universities. The panel will recommend projects for NIF managers to approve. Says Boyd, "We're hoping to see proposals for prize-winning-caliber experiments."

Once a project is approved, its external principal investigator will work with a NIF liaison physicist to generate shot requirements and target specifications. The liaison physicist will serve as a point of contact between the external team and the Integrated Experimental Team in NIF's Physics and System Engineering organization, which will help implement the experiments. In addition, external users will be available to field their own diagnostics.



In an experiment during the NIF Early Light campaign, scientists precisely measured selected areas of light (denoted by four squares) from a quad of beams firing into a gas-filled hohlraum. The outer halo represents diffuse scattering of laser light. (Image courtesy of Chan Joshi, University of California at Los Angeles.)

Three Teams Pave the Way

Three participating research teams received seed grants from Livermore to design configurations and targets for shots in HED regimes. The first team will study planetary interiors such as those found in Jupiter and Saturn. This team's principal investigator is Raymond Jeanloz from the University of California (UC) at Berkeley, and Livermore physicist Gilbert Collins is serving as the NIF contact. Other team members include Thomas Duffy from Princeton University, Russell Hemley from the Carnegie Institution, Yogendra Gupta from Washington State University, and Paul Loubeyre from Université Pierre et Marie Curie in France.

Former Livermore physicist Paul Drake, now at the University of Michigan, leads the second team, which will examine hydrodynamic processes, such as those that affect supernova evolution. Remington is the NIF contact for this team. Other members include David Arnett from the University of Arizona, Adam Frank from the University of Rochester, Tomek Plewa from the University of Chicago, and Todd Ditmire and Craig Wheeler from the University of Texas.

The third team will study laser–plasma interactions such as nonlinear optical phenomena—highly complex behavior that occurs when laser beams interact with large-scale plasmas. This team is led by Christoph Niemann, who holds the NIF professorship at UC Los Angeles (UCLA). Physicist Bob Kirkwood is the NIF contact. Other members include Chan Joshi and Warren Mori from UCLA; Bedros Afeyan from Polymath Research, Inc.; David Montgomery from Los Alamos National Laboratory; and Andrew Schmitt from the Naval Research Laboratory.

"We expect these teams to be among NIF's early science users and to help us work through external user issues," says Remington. A major goal for NIF managers is to find a mechanism for providing additional seed grants over the next several years so that other university teams can develop potential experiments for NIF.

One issue confronting the Laboratory is how best to manage site and electronic access for visitors while meeting NNSA's security requirements. A good model is the Jupiter Laser Facility, which provides an international academic community with access to its five laser platforms. (See *S&TR*, January/February 2007, pp. 4–11.) At Jupiter, teams of students, postdoctoral researchers, faculty, and other visitors conduct experiments under well-defined policies and procedures for safety, hazards control, and computer security. Livermore's Institute for Laser Science and Applications (ILSA) administers the Jupiter external user program. Each year, ILSA's director, physicist Don Correll, helps review several dozen proposals for Jupiter experiments. Correll will also serve as a reviewer of NIF proposals submitted by external investigators.

Because managers expect demand for NIF to be heavy, the Laboratory plans to adopt a staged approach to experiments. Before conducting full-scale experiments on NIF, research teams will test concepts,

Hydrodynamic Instabilities in Supernovae

A core-collapse supernova marks the explosive death of a massive star. A longtime focus of Livermore research efforts, supernovae involve several physical processes, including nuclear physics, general relativity, hydrodynamics, and turbulence. Supernovae leave behind gaseous nebulae, neutron stars, or black holes. Scientists hypothesize that supernovae produce nearly all the elements in the universe heavier than helium and that supernova occurrences in or near clouds of cold, molecular gas may trigger the formation of new stars.

Before turning into supernovae, massive stars have a shell-like structure. Each shell from the core outward is increasingly lighter, and the "interfaces" between shells are marked by density changes. When a massive star runs out of nuclear fuel, its core, which is composed of the elements silicon through iron, collapses under the force of gravity. This catastrophic implosion lasts only a few seconds and triggers a powerful explosion that sends a shock wave back through the star. The violent reaction produces an enormous number of neutrinos and many complex hydrodynamic effects. The resulting stellar explosion appears as a bright flash of ultraviolet light followed by an extended period of luminosity that is initially brighter than the star's entire galaxy.

As the shock wave moves out through the star, it produces nonlinear hydrodynamic instabilities—processes that are similar to those occurring when a nuclear weapon detonates. In plasma hydrodynamic behavior, gases or plasmas act as fluids but also have electric and magnetic properties. Propelled by the shock wave, fingers of matter from heavier shells penetrate into and through the overlying lighter shells, characteristic of Rayleigh–Taylor hydrodynamic instability.

Supernova 1987A occurred in the Large Magellanic Cloud, a galaxy about 160,000 light years from Earth. The outburst, which was visible to the naked eye, is the brightest known supernova in almost 400 years. (Image courtesy of the National Aeronautics and Space Administration.)

The National Ignition Facility (NIF) will replicate shock-induced nonlinear hydrodynamic instabilities in scaled laboratory experiments. The spatial and temporal scales of NIF shots will be 10 to 20 orders of magnitude smaller than those of their astrophysical counterparts. The facility's flexibility and control systems will allow researchers to study the physical interactions with a new level of detail. "Several complex hydrodynamic problems are still unresolved, which affects our understanding of supernovae," says Livermore plasma physicist Bruce Remington. "A central question is why they explode at all."

Existing supercomputer models fail to explain the amount of material ejected from deep within a star into its surrounding layers. "To understand these processes, we must develop computer codes that examine the interactions in three dimensions," says Livermore plasma physicist Freddy Hansen. "It's a challenging problem even with the most powerful supercomputers."

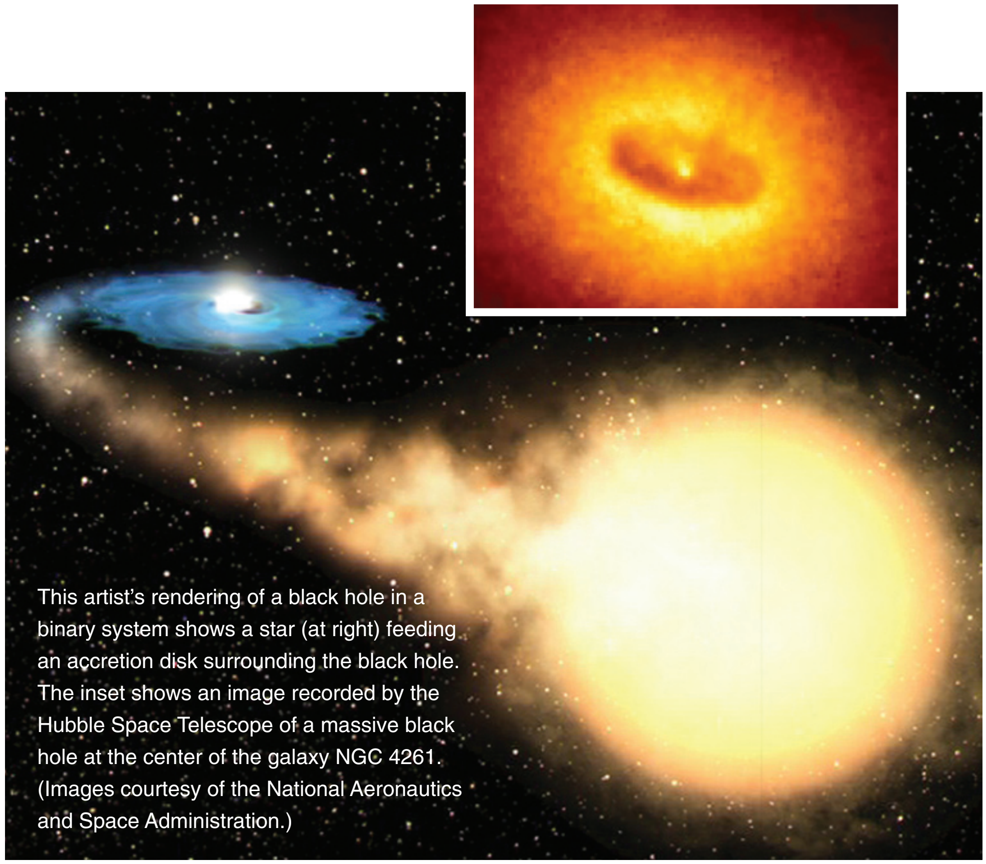
NIF research will build on two-dimensional experiments by Hansen, Paul Drake at the University of Michigan, and colleagues from the University of Rochester, University of Arizona, State University of New York at Stony Brook, and University of Chicago. In experiments with the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics, these researchers used a cylinder of beryllium, called a shock tube, filled with a layer of plastic and a layer of aerogel foam separated by a sinusoidal interface. Laser beams directed at one end of the cylinder propagate a shock through the two layers of material. The shock triggers Rayleigh–Taylor instability, which drives finger-shaped extensions of the plastic to penetrate the aerogel foam. Similar instabilities occur when the heavier inner shell of a massive star is decelerated by the lighter material nearer its surface. The subsequent hydrodynamic mixing is measured by x-ray backlighting. With this technique, some of OMEGA's 60 laser beams strike a separate disk to create an x-ray source, and the x rays generated are recorded to capture a detailed impression of the plastic layer penetrating the foam.

In a NIF experiment proposed by the Drake team, a hemispherical target of two or three increasingly lighter shells will experience a shock wave lasting 50 to 100 nanoseconds or longer, thereby causing turbulent hydrodynamic mixing. A pulse of energetic x rays will also illuminate the experiment. "The hemispherical target will allow us to experiment with the correct geometry for the first time," says Hansen.

NIF will also simulate the dynamics of supernova remnants, which produce glowing filamentary structures that can be observed for centuries. Scientists speculate that supernova remnants generate most of the cosmic rays that irradiate Earth. Laboratory experiments will help researchers to better understand the mechanisms occurring in remnants and to verify the accuracy of computational models developed to interpret supernova behavior.

targets, and diagnostics on other facilities, such as Jupiter, OMEGA, the Vulcan laser in the United Kingdom, and the Ligne d'Intégration Laser in France.

Remington points to long-standing collaboration between Livermore laser scientists and university faculty. For example, the Laboratory established a NIF Professorship Program at UCLA to foster academic partnerships and selected Niemann to hold the first professorship. Several of Niemann's graduate students are conducting research at the Jupiter Laser Facility.


This artist's rendering of a black hole in a binary system shows a star (at right) feeding an accretion disk surrounding the black hole. The inset shows an image recorded by the Hubble Space Telescope of a massive black hole at the center of the galaxy NGC 4261. (Images courtesy of the National Aeronautics and Space Administration.)

Experiment Requirements Differ

Each NIF experimental series will require different laser parameters such as wavelength, energy, and pulse duration as well as beam configurations, targets (see the article on p. 12), and diagnostic instruments. By taking advantage of the facility's experimental flexibility, teams can create a variety of physical environments. Densities can range from one-millionth the density of air to 10 times that at the core of the Sun. Temperatures can be varied from cryogenic levels (tens of kelvins) up to the core of a carbon-burning star (a billion kelvins), and pressures can be increased up to 100 terapascals. The phenomena studied will occur in fleetingly short intervals ranging from more than 1 picosecond (10^{-12} second) to fractions of a microsecond (10^{-6} second).

NIF is designed to demonstrate ignition—a burst of fusion reactions in which more energy is liberated than is input. Ignition will generate a burst of about 10^{19} neutrons in 100 picoseconds, which corresponds to a flux of up to 10^{33} neutrons per square centimeter per second, a rate at which excited-state nuclear reactions may occur. These reactions may allow scientists to study aspects of heavy-element nucleosynthesis—the process that forms elements whose nuclei are more massive than iron. (See the highlight on p. 22.)

Many science experiments will not require all 192 beams operating at maximum energy. In some configurations, groups of laser beams will irradiate a metal plate placed behind the experimental package. This plate, called a backlighter, will produce a short burst of energetic x rays to probe fine details in a fleeting moment. Other diagnostics will precisely record temporal, spatial, and spectral characteristics.

Scientists will have the flexibility required to probe plasmas—gases containing ions and electrons, the predominant form of matter in the universe. Diagnostics will measure the plasma's electron and ion temperature, charge state, electron density, and flow velocity. NIF experiments will examine the evolution of plasma perturbations at the interface of two materials. They also will investigate stable and unstable, high-Mach-number plasma flow and the transition to turbulence under extreme conditions. In addition, some experiments will study the complex behavior of nonlinear optical phenomena, which can occur when high-intensity beams interact in plasma.

"Multibeam nonlinear optical processes in plasmas are enormously complicated and can result in radiation fields that propagate at new frequencies or in new directions," says Remington. "We need to understand these processes better so we can control them more effectively on NIF."

Probing a Star's Life Cycle

Scaled NIF experiments will allow researchers to study physics relevant to the life cycle of a star, from its birth in a cold, dense molecular cloud through its explosive death and postmortem evolution. Nuclear fusion heats a star's interior, and radiation emissions cool its surface, or photosphere. The opacity of each layer controls the rate at which heat moves from the core to the surface. In this way, opacity plays a major role in determining a star's evolution, luminosity, dynamics, and stability.

Experiments will mimic stellar plasma to measure the opacities of key elements such as iron and determine how opacity changes with plasma

Photoionized Plasmas around Accreting Black Holes

One of the most fascinating objects in the universe is a so-called compact object, such as a neutron star or a black hole. Black holes are typically found in the center of a galaxy or in a binary system, associated with another star. So much mass is concentrated in a relatively small area that nothing, not even light, can escape a black hole's gravitational pull.

Supermassive black holes have rotating accretion disks, giant rings of gas and dust that can stretch hundreds of light years across. The disks have a cold outer region and an ultrahot inner region. The inner region feeds matter into the black holes. Although a black hole itself is not visible, the orbiting hot gases closest to it emit powerful x rays. Cooler material farther away emits visible radiation.

Orbiting x-ray satellites trained on black holes have recorded high-resolution spectral signatures of the hot matter as it spirals inward from the accreting disks. Researchers hypothesize that photoionized plasma causes the spectra. Typical collisional plasma is composed of a hot gas of ions and electrons caused by collisions among atoms. In contrast, photoionized plasma is caused by x rays so intense they strip electrons off elements, even in the absence of collisions.

"We believe that much of the gravitational potential energy of the in-falling matter is converted into hot, bright x rays," says Bob Heeter, a plasma physicist at Livermore. "These x rays produce the photoionized plasma we observe around a black hole."

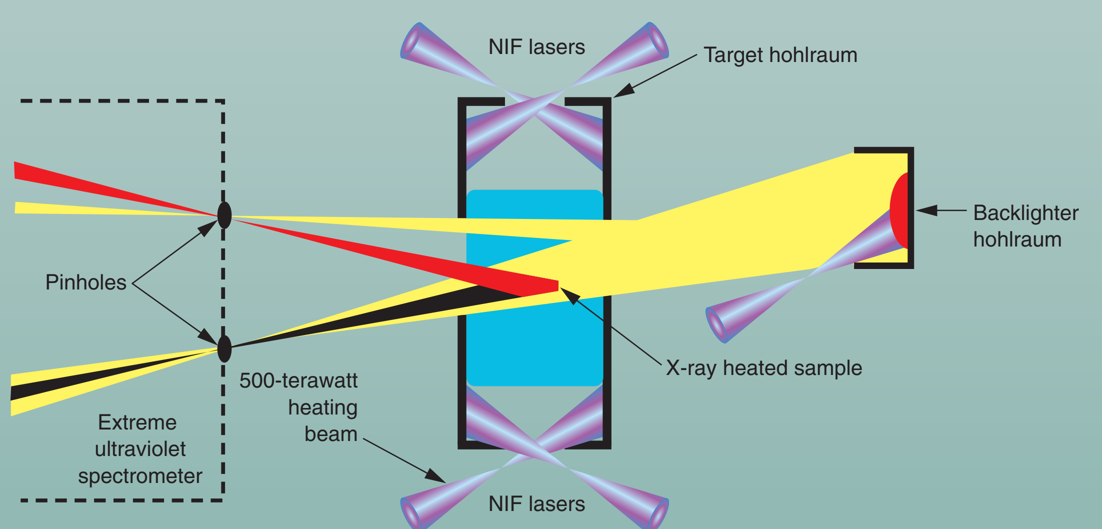
A more complete understanding of x-ray spectra could reveal the temperature, composition, flow velocity, and density of the accretion disks and the physical processes that shape them and form the photoionized plasma. However, researchers must first decipher the complex spectrum of highly ionized iron recorded by x-ray satellites. These spectra contain thousands of spectral lines that differ in frequency, depending on which electrons and how many of them the x rays have stripped from each atom.

Experiments designed for the National Ignition Facility (NIF) will produce the most extreme photoionized plasmas to be studied in a laboratory setting, allowing scientists to better interpret the data recorded by orbiting x-ray observatories. "We'll be able to help define the size, shape, and composition of the accretion disks and calculate how fast the black hole gathers matter," says NIF plasma physicist Bruce Remington. Scientists will compare the spectroscopic results to theoretical calculations and to the data recorded by x-ray satellites.

The NIF experiments will be based on techniques developed by Heeter and other Livermore physicists working with high-energy-density systems such as the Z machine at Sandia National Laboratories in New Mexico and the 60-beam OMEGA laser at the University of Rochester's Laboratory of Laser Energetics. In collaboration with colleagues from Sandia, Queen's University Belfast, Oxford University, and other institutions, Heeter used the Z machine to create photoionized plasmas of iron. However, in these experiments, the densities were higher and plasmas less photoionized than those found in space. "NIF will create intense conditions more like those found in astrophysical systems," says Heeter. The giant laser will generate an x-ray flux about 100 times greater than the Z-generated flux and impinge on iron plasmas at the same or lower density, to more closely approximate the conditions associated with black holes.

In the NIF experiments, a laser-heated gold hohlraum (a cylindrical "can") will enclose a sample of iron encased in plastic foil. The plastic will hold back the expansion of the iron plasma caused by the intense x-ray flux. Laser beams will heat the gold walls to well over 2 million kelvins, creating an intense x-ray flux for about 2 nanoseconds. The experiments will measure x-ray transmission and absorption of the iron to obtain an accurate spectral fingerprint. "Instead of the black hole, we'll use NIF as our x-ray source," says Heeter, "so we can accurately measure the radiation produced by photoionizing iron."

NIF experiments will use hohlraums to heat a sample of iron and spectroscopically diagnose it. The laser beams directed at a gold hohlraum will create intense x-ray fluxes to produce photoionized plasma. Diagnostics will measure x-ray transmission and absorption of the iron plasma.



density and temperature throughout a star's lifetime. For these experiments, researchers plan to simultaneously measure a material's temperature, density, and radiation transmission.

With such experiments, researchers can better understand stellar objects such as Cepheid variables, massive stars whose luminosities pulsate over periods of days to weeks. A remarkable feature of Cepheid variables is that their pulsation periods are proportional to their average luminosities. Astrophysicists have identified about 700 Cepheid stars in the Milky Way Galaxy, including the North Star, Polaris. Pioneering opacity experiments conducted on the Laboratory's Nova laser in the early 1990s and more recently on the Jupiter Facility lasers improved scientific understanding of Cepheid variables. (See *S&TR,* April 1999, pp. 10–17.)

Supernovae mark the death of massive stars by mechanisms not fully understood. The explosions are characterized by strong shocks and turbulent hydrodynamics. To simulate this process in scaled experiments, researchers will use laser beams to shock a hemispheric, multilayered target designed to resemble the different material layers of a supernova. Livermore scientists and colleagues from the University of Michigan and other universities have already made progress in re-creating the turbulent hydrodynamics driven by Rayleigh–Taylor instability, which is also important to weapons studies. NIF will allow researchers to conduct the first detailed three-dimensional experiments of strong-shock-induced Rayleigh–Taylor instability. (See the box on page 8.)

Black holes are one of the most exotic objects in the universe. Understanding the dynamics of matter as it spirals inward toward a black hole is an enormous scientific challenge. NIF will create photoionized plasmas to test models and improve interpretations of x-ray data recorded by space-based observatories of accreting black holes and neutron stars. (See the box at left.)

Astrophysicists are also interested in determining how planets are formed and characterizing their interior structures. NIF experiments will duplicate the physical regimes at the interiors of the planets in our solar system and the more than 200 planets discovered beyond it. (See the highlight on p. 20.) Experimental data on the equation of state and other properties of hydrogen and helium are needed to test models of the interiors of Jupiter and Saturn. Scientists will also use NIF to better understand the interior structures of the giant ice planets Uranus and Neptune.

Another planned experiment will address the properties of dust grains, which control the cooling rate of young galaxies. Dust particles range in size from nanometers to micrometers. Scientists want to determine what mechanisms, such as shock processing and collisions among grains, affect particle size. One approach is to examine how shock waves affect interstellar dust. Researchers also want to study the damage mechanisms that occur when interplanetary dust particles traveling at hypervelocity—tens of kilometers per second—slam into space hardware. Experiments on NIF would launch a strong shock wave through a reservoir of lightweight foam loaded with dust particles on its backside. As the strong shock breaks through the back of this reservoir, dust particles would be accelerated to high velocities and impact surrogate space hardware or be captured in aerogel.

Future Frontiers

"A lot of very bright people will be using NIF," says Boyd. "Over the next few years, we will see many new ideas for doing science on this system. The best are likely yet to emerge."

Correll notes that NIF represents an important new tool for HED science. "Three nominal steps are required to conduct great experimental science: build a new tool, create a new controlled environment, and produce new insight from experimental data," says Correll. "NIF achieved these steps during the Early Light campaign. When all 192 beams are available, researchers will have the experimental capabilities to conduct discovery-class science."

The new facility is sure to advance a host of physical and material science disciplines, says Remington. As a result, when astronomers point their telescopes to the sky or interpret data from space-based observatories, they will know with much greater certainty what they are seeing and sensing.

—Arnie Heller

Key Words: backlighter, black hole, Cepheid variable, equation of state, high-energy-density (HED) physics, hohlraum, hydrodynamic instability, ignition, Institute for Laser Science and Applications (ILSA), Jupiter Laser Facility, National Ignition Facility (NIF) Early Light campaign, OMEGA laser, photoionized plasma, Rayleigh–Taylor instability, supernova, Z machine.

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